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Recycle Requirements for NASA's 30 cm Xenon Ion Thruster

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Recycle Requirements for NASA's 30 cm Xenon Ion Thruster

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Electrical breakdowns have been observed during ion thruster operation. These breakdowns, or arcs, can be caused by several conditions. In flight systems, the power processing unit must be designed to handle these faults autonomously. This has a strong impact on power processor requirements and must be understood fully for the power processing unit being designed for the NASA Solar Electric Propulsion Technology Application Readiness program. In this study, fault conditions were investigated using a NASA 30 cm ion thruster and a power console. Power processing unit output specifications were defined based on the breakdown phenomena identified and characterized.

Introduction

Ion thruster systems can provide specific impulse levels unattainable with state-of-art propulsion systems and are currently being considered for applications ranging from Earth-space orbit raising and repositioning to primary propulsion for planetary missions.[1] The NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) program is developing a 30 cm xenon ion subsystem capable of operation from 0.5 kW to 2.3 kW.

A schematic diagram of an ion propulsion system is shown in Figure 1. From this, it can be seen that a power processing unit (PPU) must provide several electrical outputs required to run the thruster. High voltage breakdowns, or arcs, are anticipated in the course of normal thruster operation.[2-5] The PPU must be robust enough to withstand the initial transient associated with the breakdown, rapidly clear the fault, and return the thruster to its steady-state operating condition.

When an electrical breakdown occurs, a large amount of current is drawn out of the high voltage power supplies which can collapse their output voltage. This will disable the acceleration mechanism, erode surfaces in the thruster, and possibly damage components in the power supplies. There are many high voltage surfaces in the thruster (see Figure 1) where arcing can originate. The discharge chamber anode is at the ion beam potential, and the discharge cathode and its assembly are at a slightly lower potential. The screen grid, although mechanically isolated from the rest of the thruster, is at a potential comparable to anode potential. The neutralizer cathode provides electrons a path to the ionized plasma or to any other surface at a high potential under some abnormal conditions.

When arcing occurs, a recycle sequence (turn-off / turn-on sequence) should be performed in the power supplies to extinguish the arcs and restore nominal operation of the thruster. This recycle sequence should be as fast as possible to minimize recycle impacts on thruster operation and involve the fewest number of steps to minimize complexity. Regardless of this sequence, the PPU should be capable of handling the

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initial transient resulting from the breakdown.

Electron backstreaming from the neutralizer occurs when the accelerator voltage decreases before the beam voltage is removed during a recycle or when it is applied after the beam voltage during recycle recovery.[2-6] Depending on the power supply configuration being used, electron backstreaming can result in damage to the PPU or can cause an unsuccessful recycle. This makes beam/accelerator power supply synchronization critical in order to obtain successful and reliable recycles.

The objectives of the study reported in this paper were to determine PPU output requirements which reliably address arcing. For this, a 30 cm thruster was used, and several common fault conditions were simulated. These were successfully characterized, and the efficacy of the selected recovery sequence was demonstrated. The information is transportable to the NSTAR PPU design effort.[7]

Apparatus

Thruster

The 30 cm diameter xenon ion thruster, described in detail in reference 1, was used for the high voltage recycle tests reported herein. It is presently a functional model capable of operating between 0.5 kW and 5.0 kW which exceeds the maximum thruster power level of 2.3 kW for the JPL / NASA LeRC NSTAR program.

One distinctive feature of the NASA 30 cm ion thruster is the lack of a discharge cathode keeper electrode. This simplifies thruster and PPU designs. In addition, the thruster design eliminates parts, found in other thrusters, that may be susceptible to high erosion rates due to close proximity to the discharge cathode. On the other hand, the absence of the discharge cathode keeper does not allow the discharge cathode emission to be turned off during a recycle. Instead, the discharge current is only reduced. The minimum current necessary to maintain a stable discharge requires the accelerator supply to handle a larger impingement current during a recycle than in the case when thrusters employ keeper electrodes. There also is a maximum current at which the discharge emission can be maintained without the occurrence of continuous recycles due to the high plasma density.

Power Console

A 5KW power console, developed for the NASA Electric Propulsion Outreach Program, was used to provide all the electrical and control functions required to operate the thruster.[4] It consists of six commercial power supplies, two cathode ignitors, and a control and telemetry unit contained in a standard 48 cm wide laboratory rack. Each individual power supply is used to provide one of the six electrical outputs. The control and telemetry unit controls the power supplies and monitors the outputs of the beam and accelerator power supplies for fault occurrence. If a fault is detected, a turn-off / turn-on sequence or recycle is performed to eliminate arcing and restore nominal operating conditions. A block diagram and a photograph of the power console are shown in Figure 2 and Figure 3, respectively.

The characteristics of the beam and accelerator power supplies were relevant to the recycle study conducted herein. The beam supply maximum output is 1500 V at 3.3 A and the accelerator supply is 600 V at 1.6 A. The output of the accelerator supply is heavily filtered with capacitors giving it a considerable instantaneous current capability.

The general recycle sequence implemented in NASA's power console consists of several events.[4] Once either a high beam or accelerator current is detected, a 100 ms delay occurs. This is to facilitate the study of the short circuit conditions and can be eliminated from the sequence. Then, the beam supply is turned off and simultaneously the discharge supply output current is reduced to a predetermined value. After another 100 ms, the accelerator supply is turned off. This delay in turning off the accelerator supply is critical to avoid electron backstreaming to positive potential surfaces. After another 300 ms, the restoration of the nominal conditions starts. At this time, the accelerator supply is turned on, and 100 ms later the beam supply is turned on. Again, this delay in turning on the beam supply was to avoid electrons from the neutralizer backstreaming to positive potential surfaces. Finally, the discharge supply returns to nominal conditions 400 ms later. The total time for the recycle sequence is approximately 1.0 sec. A plot of a successful recycle on a 30 cm thruster is shown in Figure 4.

Facility

The functional model ion thruster was evaluated in a 4.6 m diameter and 19.2 m long vacuum chamber and is described in detail in reference 8. It used fifteen of its twenty 0.8 m diameter oil diffusion pumps and a 27 m^2 surface area helium cryopanel to produce pressures as low as 2.7 x 10^{-5} Pa (no-load) and about 1.7 x 10^{-4} Pa at a thruster power of 2.3 kW for the tests reported herein.

Procedure

The parameters of interest for this test were beam and accelerator voltages and discharge current, which were directly affected by the recycle sequence done by the power console, and beam and accelerator currents, which were directly related to the ion acceleration mechanism in the thruster. The discharge voltage was not studied because it was primarily affected by the discharge cathode flow, but not by the breakdown phenomenon. Measurements were obtained using a 3 GHz bandwidth digitizing oscilloscope. A current probe was located at one of the output terminals of each power supply to measure current, and 100x probes for the beam voltage and 10x probes for the accelerator voltage were located across the output terminals of the respective power supply to measure voltages differentially.

The power console was initially tested using a resistive load to determine its capability of surviving fault conditions in the thruster. This was done using a shorting rod and simulating short circuits between engine parts and ground. No problems caused by the faults were identified and the recycle sequence performed according to the specifications.

Resistive load testing can provide information about the functionality of the power console, but cannot completely simulate all the conditions caused by a fault. On an operating ion thruster, the collapse of a high voltage power supply output increase the impingement current on the grid biased by the other high voltage power supply. Inappropriate sequencing of the power supplies during a recycle can lead to repeated faults. Testing with a thruster was therefore necessary to verify these other conditions.

Testing was continued using a 30 cm thruster. The hollow cathodes were adequately conditioned, discharges ignited, and the high voltage to the thruster was activated to start beam extraction. The thruster was run for approximately 30 minutes to allow thermal stabilization. Data were obtained for intentional short circuits from anode to ground, accelerator grid to ground, and screen grid to accelerator grid during high power operation of the thruster. This high power condition is more demanding on the recycle requirements than low power operation due to high ion density in the discharge chamber and higher beam and accelerator voltages and currents. Even at the highest power condition for the NSTAR ion propulsion experiment of 2.3 kW, real thruster recycles were infrequent. The input power and flow rates for this operating condition are shown in Table 1.

Results and Discussion

Various shorts can occur in an ion thruster. Breakdowns between the screen and accelerator grids are by far the most common arcing phenomenon and periodically occur during thruster operation. Other shorts like those due to insulation or propellant isolator failures, erosion, or environmental effects, also can occur and are often associated with thruster wearout or failure. The PPU must also be able to handle these arcs as it is desirable that one PPU be able to operate multiple thrusters. Figure 5 shows the shorts that were simulated and are discussed below.

Figures 6 through 8 show the parameters of interest during the recycles caused by the simulated faults. Beam and accelerator currents are shown in the top of the figures and beam and accelerator voltages, which share the same zero reference, and the discharge current are shown in the bottom.

The first fault simulated was an anode to ground short. This kind of short can be caused by a main propellant isolator or other insulation failure.[9] Figure 6 shows that when the arcing occurred, the beam current increased causing a collapse of the beam voltage. This high beam current was detected, and a recycle sequence was started. Due to the delay on the recycle detection, the discharge current did not cut back until approximately 100 ms later. This maintained a high ion density in the discharge chamber which lead to increasing the accelerator impingement current because the collapse of the beam voltage defocused the ion beam and more ions impinge on the accelerator grid. Approximately 600 mA and a peak of 1.0 A of accelerator current was needed to go through a recycle without loading down the accelerator supply and causing electron backstreaming. Once the recycle sequence started and the discharge current was reduced to 4.0 A, only approximately 100 mA of accelerator current were drawn from the supply. In this case this current came from the output capacitors on the accelerator supply that remain charged because the supply had the capability to supply the current needed during the short circuit. This current slowly reduced the magnitude of the accelerator voltage until the power supply was commanded on about 900 ms after the recycle started. As soon as the beam supply was commanded on, the ions leaking out of the discharge chamber became focused and the accelerator impingement current returned to a low steady-state value. When the discharge current was increased to its steady-state value, the beam current also increased, and the thruster returned to steady-state conditions.

An accelerator grid to ground short was also simulated. This can be caused by an insulation problem or loose sputter-deposited facility material.[5] Figure 7 shows that when the accelerator grid short occurred the accelerator current increased rapidly to a value higher than 1.8 A which activated a recycle sequence. This was higher than the maximum output of the power supply, but in this case the current was supplied by the output capacitors of the power supply. This collapsed the accelerator voltage to approximately -60 V causing electron backstreaming which can be seen as an increase in beam current. Again, approximately 1.0 A of peak accelerator current and 100 mA during the discharge cutback were needed to get through a recycle. The steps to return to steady-state conditions were similar to those described above for the first case.

The last fault condition simulated was an accelerator grid to screen grid short. This typically results from the growth of small protrusions on the grids caused by ion bombardment or by loose sputter-deposited thruster material. When this kind of short circuit occurs, the floating screen grid is biased to accelerator grid potential. This causes most of the ions leaving the discharge chamber to impinge on the screen grid. Figure 8 shows that the accelerator voltage, beam voltage, and beam current stayed close to their respective steady-state values, but the accelerator current increased to a value of more than 1.8 A which initiated a recycle sequence. This should be enough to collapse the accelerator voltage, but the current was apparently supplied by the output filter of the accelerator power supply. Once the simulated short was released and during the detection delay, approximately 1.0 A of accelerator current was drawn from the power supply and then dropped to 100 mA during the discharge cutback. The rest of the recycle sequence events were similar to those described for the other cases.

For the three cases simulated, the discharge current during a recycle was reduced to a level of 4.0 A. The ion density sustained by this discharge caused an impingement current on the accelerator grid of approximately 100 mA. At the time of this writing, only this operating point had been investigated. Work will continue to study the accelerator current requirement at higher discharge cutback currents and to determine the maximum cutback current that can be used for obtaining a successful recycle.

Conclusion

The occurrence of short circuits in an ion thruster is probable due to both the high voltages used to accelerate ions and to protrusions from sputtered material that form in the ion optics. These short circuits impose much higher current requirements on the high voltage power supplies during a recycle than the requirements for nominal operation. A recycle sequence is needed to extinguish arcs and restore nominal conditions in the thruster. Output filtering on the power supplies also affects the transient response of the power supplies during recycles.

Recycles were obtained simulating short circuits from anode to ground, accelerator to ground, and screen grid to accelerator grid. During these recycles the accelerator impingement current was approximately 100 mA, with a 1.0 A surge, for a discharge current of 4.0 A. The accelerator power supply must be capable of providing this current to ensure a successful recycle and to avoid a voltage collapse that could lead to electron backstreaming. Some of this current was supplied by the output filter capacitors of the accelerator power supply. These requirements have a critical impact on the design of the accelerator power supply and the recycle sequence to be implemented in the PPU for the NSTAR experiment. Work will continue to quantify accelerator current during recycles at higher discharge current cutback values.

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V_{beam}	1100 V
V_{accel}	-180 V
V_{dis}	28 V
$V_{neut\ kpr}$	17 V
I_{beam}	1.7 A
I_{accel}	6 mA
I_{dis}	14 A
$I_{neut\ kpr}$	2 A
m_{main}	22.2 sccm (20°C)
m_{cath}	1.82 sccm (20°C)
m_{neut}	3.63 sccm (20°C)
P_{total}	2300 W

Table 1. High power operating conditions for NSTAR experiment

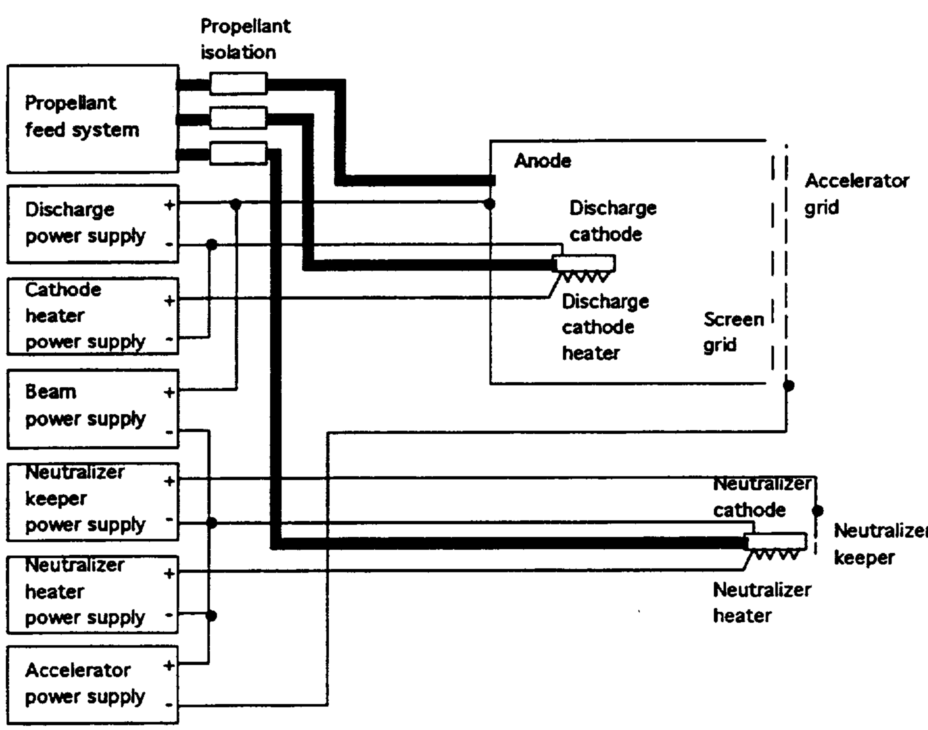

Figure 1. Xenon ion propulsion subsystem

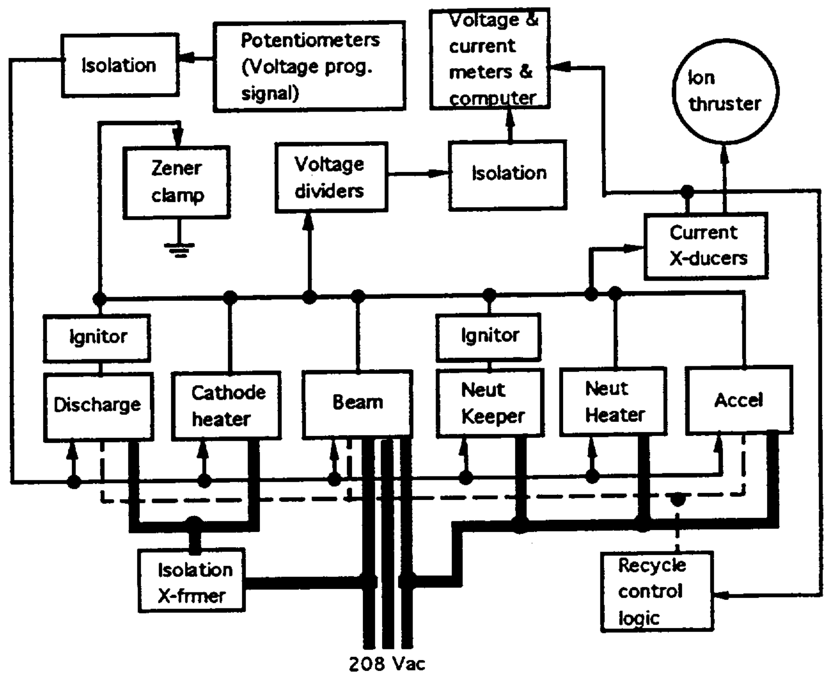

Figure 2. Power console block diagram

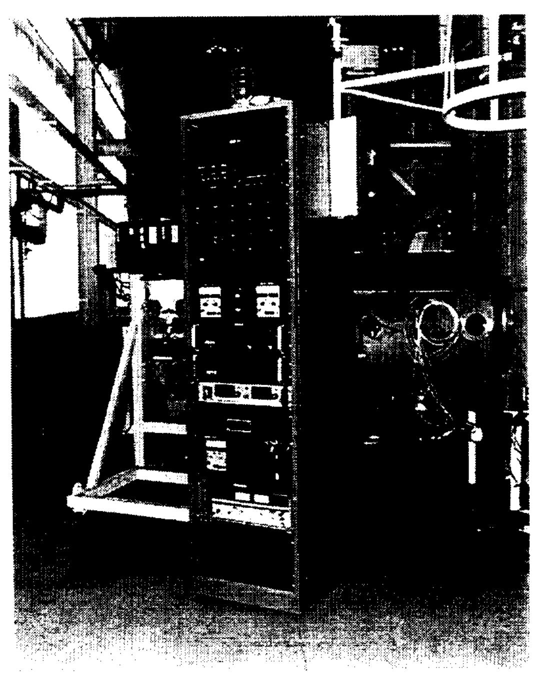

Figure 3. 5 kW power console

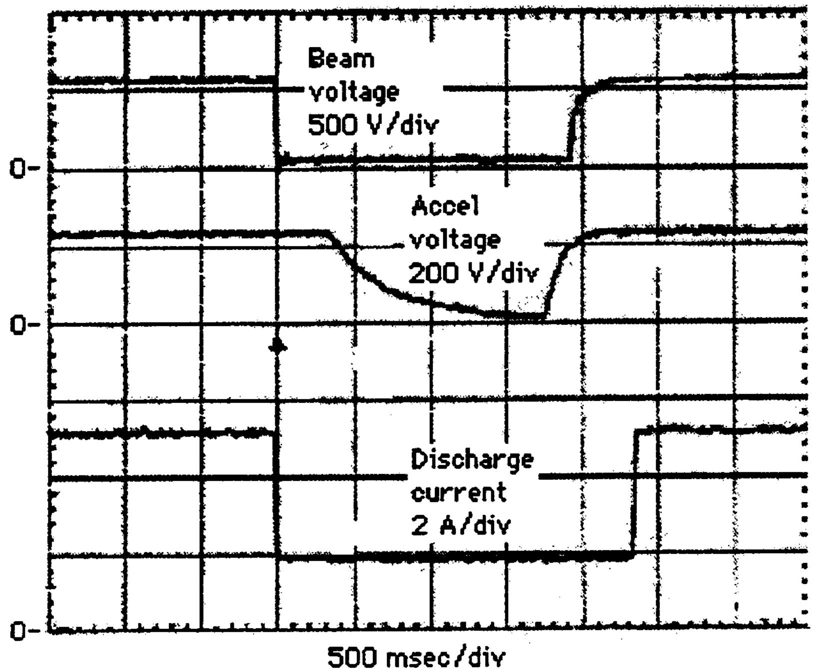

Figure 4. Recycle sequence on 30 cm thruster

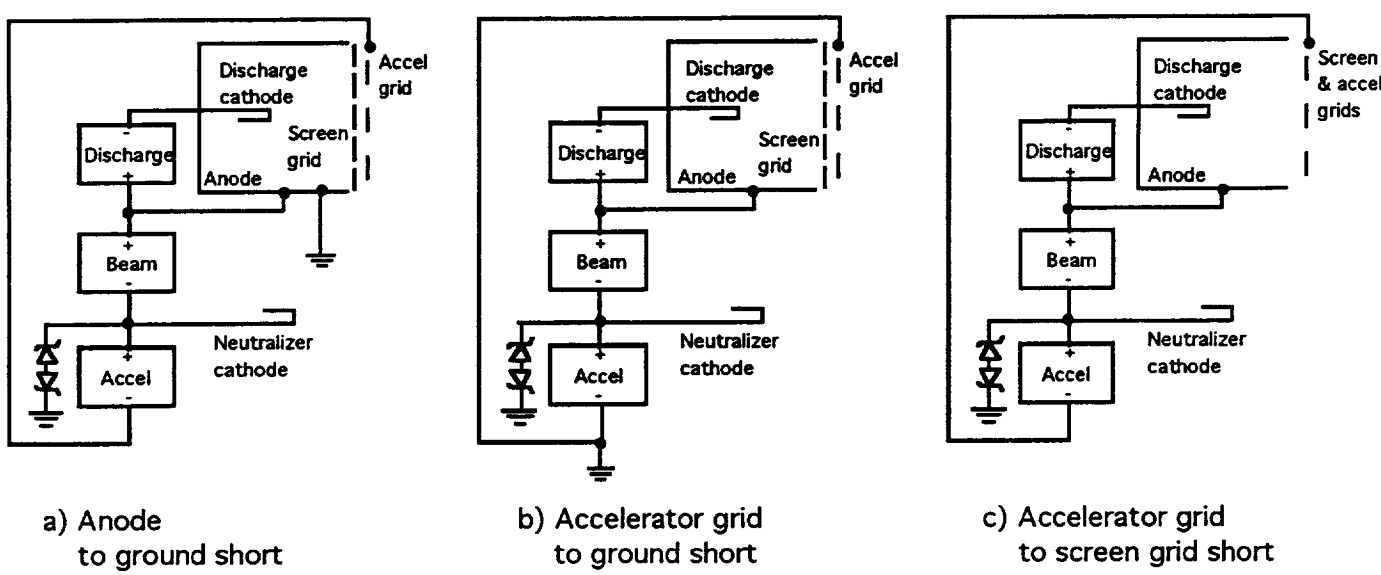

Figure 5. Equivalent schematics of simulated shorts

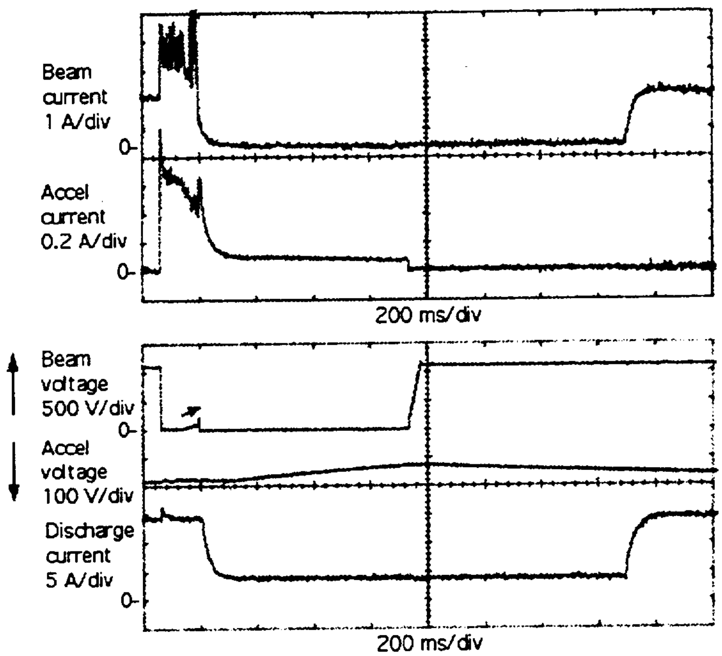

Figure 6. Anode to ground short circuit on 30 cm thruster

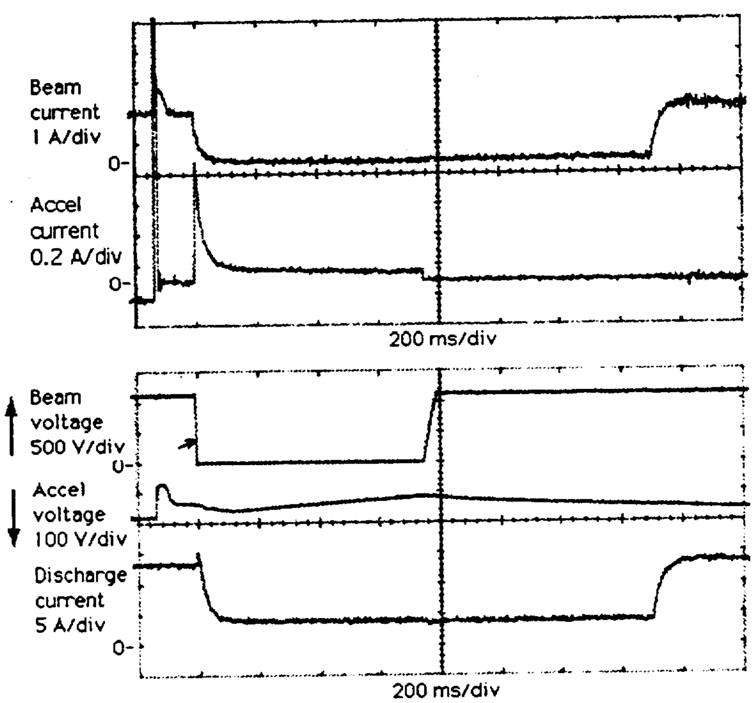

Figure 7. Accelerator grid to ground short circuit on 30 cm thruster

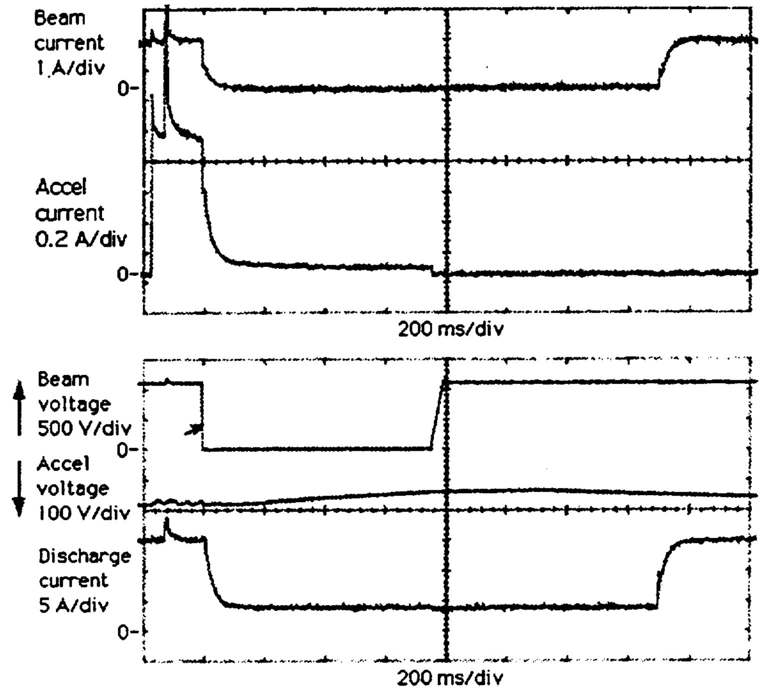

Figure 8. Accelerator to screen grid to short circuit on 30 cm thruster

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13. ABSTRACT *(Maximum 200 words)*

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